GROWTH OF ECCENTRICITIES AND INCLINATIONS OF PLANETESIMALS DUE TO THEIR MUTUAL GRAVITATIONAL INFLUENCE.

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Formation of trans-Neptunian objects and planetesimals: The total mass of the present Edgeworth-Kuiper belt is estimated to be $0.01m_\oplus$ [1] or $0.1m_\oplus$-$0.2m_\oplus$ [2-3], where $m_\oplus$ is the mass of the Earth. The total mass of the initial belt can be about $10m_\oplus$-$50m_\oplus$ [4-5]. The mass of the present asteroid belt is estimated to be $\sim 2.5 \cdot 10^{-4} m_\oplus$ [6], and its initial mass could exceed several $m_\oplus$.

It is considered [5,7-8] that the process of accumulation of trans-Neptunian objects (TNOs) took place at small ($\sim$0.001) eccentricities and a massive belt. For example, Stern [5] and Stern and Colwell [7] showed that 100-1000 km TNOs could be formed from 1-10 km planetesimals only at eccentricities $e<0.002$ and the total mass of the belt $M_S>10m_\oplus$. Kenyon and Luu [8] obtained runaway growth in 100 Myr for e=0.001 and in 700-2000 Myr for e=0.01 at $M_S \geq 10m_\oplus$. These times are greater than the time of formation of the massive Jupiter, which did not exceed several tens of Myr. We considered [9] that such small eccentricities could not exist during a large time span, both due to the gravitational influence of the forming giant planets and due to the mutual gravitational influence of TNOs. Our runs showed [9] that under the gravitational influence of the giant planets, maximum eccentricities of TNOs always exceed 0.05 during 20 Myr. Gas drag could decrease eccentricities of TNOs and planetesimals, and the gravitational influence of the forming giant planets could be less than that of the present planets. Nevertheless, in our opinion [9-12], it is probable that, due to the gravitational influence of the forming giant planets and migrating planetesimals, small eccentricities of TNOs could not exist during all the time needed for accumulation of TNOs with diameter $d>100$ km.

We support [9-12] the suggestion [4] that some TNOs with $d>100$ km could be formed directly by the compression of large rarefied dust condensations with semi-major axis $a>30$ AU, but not by the accretion of smaller solid planetesimals. We also suppose that some planetesimals with $d\sim$100-1000 km in the feeding zone of the giant planets and with $d\sim$100 km in the terrestrial planets' zone and some large main-belt asteroids could also be formed directly by such compression. Some smaller objects (TNOs, planetesimals, asteroids) could be debris of larger objects, and other such smaller objects could be formed directly by compression of condensations. Even if at some instants of time at approximately the same distance from the Sun, the sizes of initial condensations, which had been formed from a dust layer due to gravitational instability, had been almost identical, there was a distribution in masses of final condensations, which compressed into the planetesimals. As in the case of accumulation of planetesimals, there could be a "run-away" accretion of growing condensations and there was a distribution in masses of the final condensations. It may be possible that, during the time needed for compression of condensations into planetesimals, some largest final condensations could reach such masses that they formed planetesimals with diameter equal to several hundreds kilometers. Formation of large TNOs from dust condensations allows one to understand the observed difference between TNO binaries and asteroid binaries [12-13].

In the models of accumulation of planets, several authors considered the mutual gravitational influence of planetesimals. Ipatov [13-15] simulated the orbital evolution of 3 or 4 gravitationally interacting objects with masses close to that of Pluto moving around the Sun in one plane. Results of simulation of the evolution of disks of bodies showed [16-18] that the mean eccentricities e_m of planetesimals in the zone of the giant planets were about 0.3 during the main part of the accumulation of Uranus and Neptune.

Initial data: Below we study the variations of eccentricities and inclinations of 100-1000 km objects-planetesimals due to their mutual gravitational influence. These studies are based on results of integration of the orbital evolution of N=50 gravitationally interacting identical objects-material points moving around the Sun. The symplectic code from the integration package SWIFT [19] was used. In one series of runs, masses of objects were the same as those of bodies of density ρ=2 g/cm^3 at d=1000 km; in another series of runs, d=100 km. Initial eccentricities and inclinations were equal to 0.0001 and 0.00005 radian, respectively. Initial values of a were varied with a step d_a equal to $0.01a_o$ or $0.001a_o$ (in each run, d_a was constant) at d=1000 km and with a step equal to $10^{-5}a_o$ or $10^{-6}a_o$ at d=100 km, where a_o is the initial semi-major axis of the orbit of the 'first' object. The considered able 1: Mean eccentricities e_m and mean inclinations i_m (in degrees) at several values of time.

d, km	1000	1000	100	100
d_a/a_o	0.001	0.01	10^{-6}	10^{-5}
		e_m		
t/t_o=10^4	0.010	0.00016	0.008	0.0053
t/t_o=10^5	0.015	0.00019	0.008	0.0054
t/t_o=10^6	0.038	0.00035	0.008	0.0056
t/t_o=10^7	0.081	0.018	0.009	0.0064
$5 \cdot 10^7$	0.091	0.046	0.010	0.0077
t/t_o=10^8	0.11	0.055	-	0.0094
		i_m		
t/t_o=10^4	0.11	0.0029	0.0068	0.0092
t/t_o=10^5	0.24	0.0028	0.011	0.017
t/t_o=10^6	0.7	0.0028	0.035	0.028
t/t_o=10^7	1.47	0.058	0.060	0.064
$5 \cdot 10^7$	2.19	1.13	0.111	0.091
t/t_o=10^8	2.25	1.77	-	0.125

time span was $\sim(10^8\text{-}6{\cdot}10^8)t_o$, where t_o is the time of one revolution around the Sun at a=a_o.

Results of runs: The mean eccentricities e_m and mean inclinations i_m of objects at several values of time t are presented in Table 1. If initial orbits of some pairs of objects allowed their close encounters (all runs considered, exclusive for d_a=$0.01a_o$), then during 10^3t_o, e_m increased up to 0.005-0.007 for both values of d (the growth of i_m was up to 0.03^o at d=1000 km and up to 0.003^o at d=100 km). Such jumps of eccentricity for almost circular initial orbits were caused by the 'exchange' of semi-major axes of two objects encountering each other with a very small relative velocity [16].

For d_a=$0.01a_o$ and d=1000 km, initial orbits were relatively far from each other, and at t<10^6t_o, there were no close encounters, $e_m \leq 0.0003$, and $i_m \leq 0.003^o$. For d=1000 km at t=10^8t_o, e_m reached 0.05 and 0.11 (and i_m increased up to 1.7^o and 2.3^o) at d_a=$0.01a_o$ and at d_a=$0.001a_o$, respectively. For d_a=$0.01a_o$ at t=$6.3{\cdot}10^8t_o$, e_m reached 0.13 and i_m reached 3.6^o. For d=100 km, the growth of e_m and i_m during 10^8t_o was smaller by an order of magnitude than that for d=1000 km. At t/t_o=10^8 for the second, third, and fifth columns of Table 1, the ratio e_m/i_m (for i_m in radians) equals to 2.8, 1.8, and 4.3, respectively.

Dependence of e_m and i_m on the number of objects: The number of planetesimals (or TNOs) in the real disk was large, and the growth of e_m and i_m could be faster than that for the above runs at N=50. For a disk of identical objects, we can approximately consider [18] that e_m and i_m are proportional to $N_{en}^{1/2}$, where N_{en} is the number of close encounters of objects. At d=1000 km, the mass of one object is about $1.736{\cdot}10^{-4}m_\oplus$. The total mass of 50 such objects is less than $m_\oplus$ by a factor of 115, and the time needed for a growth of e_m to some value at N=50 will be greater by about an order of magnitude than that for such objects with a total mass m_S=$m_\oplus$. For 50 objects with d=100 km, the time needed for a growth of e_m to some value will be greater by a factor of $\sim 10^{5/2} \approx 300$ than that for such objects with m_S=$m_\oplus$. Taking into account results of the runs presented above, we can conclude that for a disk of identical 100 km bodies with m_S=$m_\oplus$, e_m can reach 0.01 during t=$10^8t_o/300 \approx 3{\cdot}10^5t_o$.

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